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RELATIONSHIPS BETWEEN NEARSHORE PROCESSES AND BEACH CHANGES ALONG THE OUTER BANKS OF NORTH CAROLINA.

Louisiana State University, Ph. D., 1965
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RELATIONSHIPS BETWEEN NEARSHORE PROCESSES AND BEACH CHANGES ALONG THE OUTER BANKS OF NORTH CAROLINA

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Geography

by
Robert Dolan
B.S., Southern Oregon College, 1955
M.S., Oregon State University, 1957
January, 1965

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ABSTRACT

The purpose of the investigation was to determine the degree of association between surf-zone processes and the configuration of a natural beach deposit. A conceptual system of the inshore hydraulics is developed to describe the complex wave-tide-beach relationships. In this beach-energy model the principal interactions are associated with (1) the forces of shoaling and breaking waves, (2) variations in still-water level, and (3) characteristics of the deposit and its constituent particles.

Conceptual relationships were compared with actual beach conditions in a series of experiments conducted during 1962 on Bodie Island, North Carolina. In these experiments the design was limited to temporarily and spacially isolated segments of the total system. The beach below lowest tide was, for example, physically beyond the limits of measurement. Beach responses to the hydraulic forces were therefore studied within the zone between low tide and the limit of wave uprush.

Erosion and deposition are expressed as changes in beach thickness and width. Configuration was restricted to characteristics of the exposed subaerial beach, namely, beach-face slope. The energy factors, other than still-water level, were estimated from properties

of essentially unbroken waves; wave height, wave period, and wave direction.

Specific hypotheses that changes in beach geometry and sediments are a function of varying wave and tidal conditions were tested with multiple-regression analysis. F-tests indicate that statistically significant relationships exist for all process-response associations except those of the sediment properties. Multiple coefficients of determination range from .09 to .85; whereas, r^2 values for individual factors vary from .06 to .58. In general, these tests show that variations in the basic geometry of the beach deposit can be predicted with a reasonable degree of accuracy by using two independent variables, wave height and still-water level. Wave period and wave direction are of less importance. Although some of the associations are not as strong as initially assumed, the conceptual beach-energy model is in good agreement with the Bodie Island natural beach data.

Residual variance is attributed to (1) variables not included in the experiment, (2) inadequacies in the sampling design, (3) time-delay between changes in the process intensity and resulting beach-face adjustments, and (4) undetected measurement errors.

INTRODUCTION

Rapid development of public and private coastal property since the end of World War II has emphasized the need for a better understanding of coastal and beach processes. Oceanic beaches are areas of constant and sometimes catastrophic changes, leading to serious economic and human consequences. Within 72 hours during March of 1962 a violent storm took 32 lives and resulted in 200 million dollars damage along the Atlantic Coast.[1] In addition to the human and economic factors, beaches are especially interesting to the geomorphologist since they are among the most dynamic of the physical environments. The balance between erosion and deposition is delicate, with changes occurring continuously and at varying rates. For this reason beaches are commonly classified with the most variable of geomorphic forms (King, 1959, p. 1).

Although there is clearly adequate justification for beach research, the literature reveals relatively few detailed studies of natural beach processes. With the exception of laboratory experiments, research in the coastal field has been more qualitative than quantitative.

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[1]A description of coastal changes and atmospheric conditions during the "Great Atlantic Storm" is given by Cooperman and Rosendal (1962), Podufaly (1962), Stewart (1962), U. S. Army Engineers (1962), O'Brien and Johnson (1963), and Bretschneider (1964).

Therefore, this investigation was undertaken to examine the association between surf-zone processes and beach changes as they occur in nature. A conceptual model[2] was formulated from both the literature and field experiences to establish the assumed significance for the principal elements of interaction within the beach environment. An experiment was designed to test the model on a natural beach in North Carolina. Finally, these observations were compared with the associations suggested by the model.

CONCEPTUAL MODEL OF BEACH-ENERGY SYSTEM

Reduced to a fundamental level, the general dynamics of a beach[3] can be described by three major elements: the beach deposit, water, and zone of water and deposit interaction. A generalized diagram of this preliminary model is shown in Figure 1. The deposit is a static mass of particles small enough to be placed in motion by

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[2]Among the more recent papers concerning process-response models are: Miller and Zeigler (1958), Krumbein (1964), Whitten (1964), and Whitten and Boyer (1964).

[3]Complete beach terminology is outlined by Wiegel (1953). Definitions for "beach" have varied considerably over the past decades. Investigators concerned mainly with classification and description have developed fairly rigid nomenclature, commonly shown as a beach profile. For example, see Johnson (1919, p. 162), Kuenen (1950, p. 268), Guilcher (1958, p. 79), and Shepard (1958, p. 76). In this report "beach" is considered (King, 1959, p. 1) "an accumulation of loose material around the limit of wave action.....extending from the extreme upper limit of wave action to the zone where the waves, approaching from deep water, first cause appreciable movement of the bottom material."

hydraulic forces, and collectively arranged to produce a morphology unique to the beach environment. Water is the direct medium through which energy, in wave form, is transmitted to the deposit from the ultimate generating force, the wind. Finally, when motion is introduced to the water a zone of interaction is generated between the water and deposit; the resulting dynamic system is here defined as the beach-energy system. The main focus of interaction, which occurs along an interface where the sea and deposit meet, is restricted neither to time nor space, but migrates temporarily and spacially in response to beach changes and the rise and fall of the tides.

Zonal Model of Beach-Energy System

Given a general system composed of water and deposit interactions, the preliminary model may be further described in the form of three dynamic and areally distinct zones based on the degree and kind of water and deposit interaction.[4] A cross-section of such a hypothetical beach, composed of an (1) offshore zone, (2) region of shoaling and breaking waves, and (3) subaerial beach, is illustrated in Figure 2.

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[4]Similar zonal divisions may be seen in Johnson (1956), Miller and Zeigler (1958), King (1959), Kemp (1960), and Krumbein (1964).

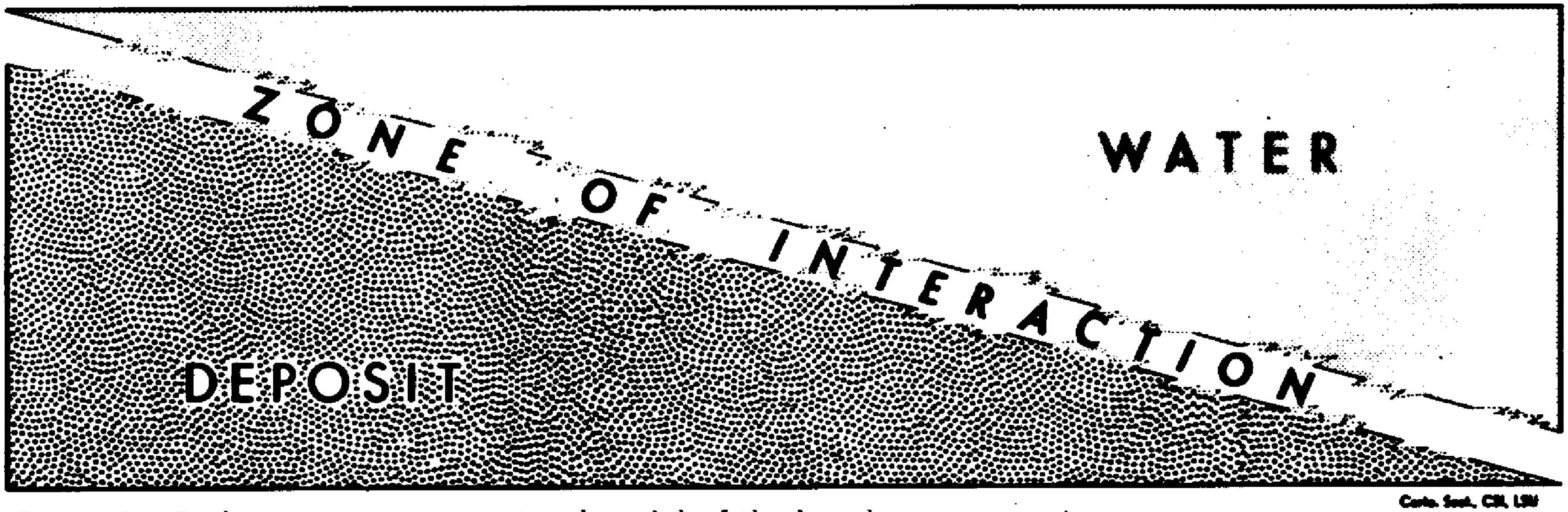

Figure 1. Preliminary cross-sectional model of the beach-energy system.

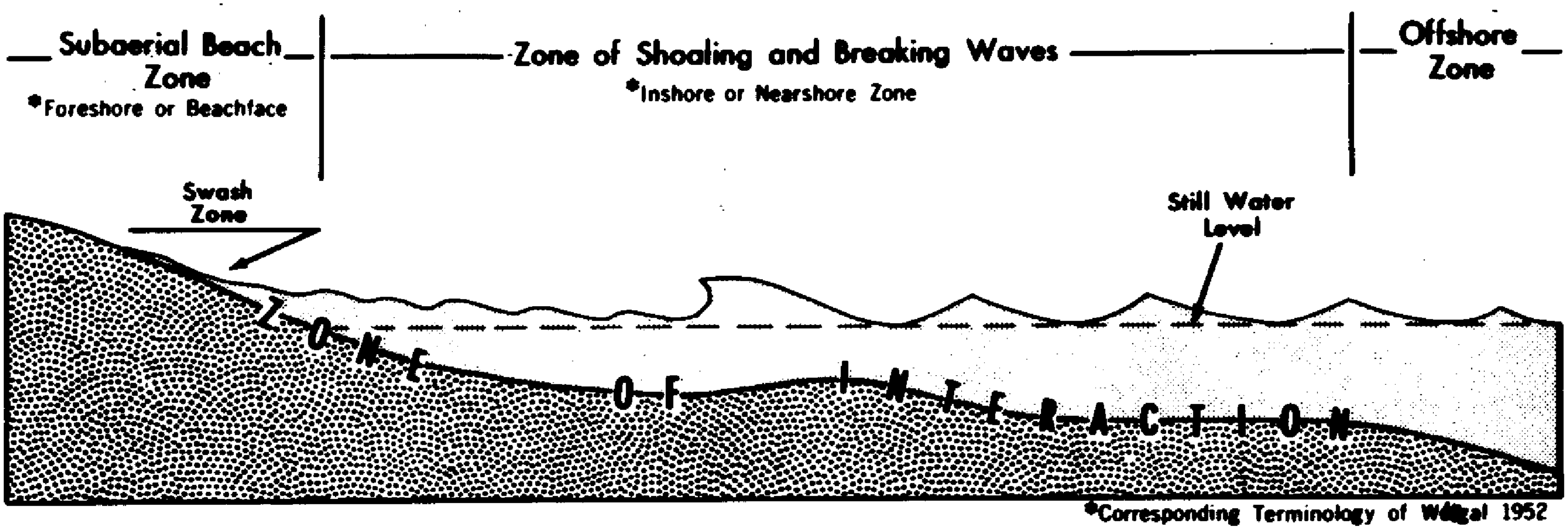

Figure 2. Zonal model of the beach-energy system.

The Offshore Zone

In the offshore zone, water motion is essentially oscillitory[5] and interaction with the bottom is minor. The morphologic pattern consists of a uniform seaward slope, reflecting long-term trends in the wave-tide regime rather than short-term sea state conditions.

The Zone of Shoaling and Breaking Waves

Strong interaction between water and deposit is characteristic of the zone of shoaling and breaking waves. As oscillatory waves advance from offshore, a point is reached where water motion associated with the wave reaches bottom. Continued shoreward movement causes the deep-water waves to undergo several changes, most important to which are shoaling and breaking.[6]

Shoaling begins at a water depth approaching half wave-length. From this point shoreward deformation is continual until breaking occurs. Breaking is mainly dependent on wave characteristics and usually takes place at a water depth of between 1 and 1.5 wave height, or when water particle velocity near the crest exceeds the rate of wave advance.

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[5]For more detailed discussion of deep-water wave action see Hall and Mason (1941), O'Brien and Mason (1942), Russell and MacMillan (1952), Wiegel (1960), Beach Erosion Board (1961), Defant (1961), and King (1963).

[6]For treatment of shoaling and breaking waves see Iverson (1952), Wiegel and Fuchs (1955), King (1959), Wiegel (1960), LeMehaute (1961), and Miller and Zeigler (1964).

Waves are the fundamental source of energy in the beach-energy system, however bottom configuration plays an important role in determining the place of energy dissipation.[7] The position of breaking varies, for example, from narrow zones with maximum energy release, to wide zones through which waves retain their identity and expend energy over most of the inshore. Differences between the two conditions are attributed mainly to a complex relationship between nearshore bottom slope, water depth, and wave characteristics. Hence, steep gradients result in concentration of energy closer inshore, whereas, flat profiles have the effect of forcing energy dissipation over a proportionately wider zone. In addition to general slope - water depth relationships, well-defined longshore or break-point bars often result in distinct breaker lines along which a high percentage of incoming wave energy may be released.[8]

Water - deposit relationships of shoaling waves are rather well known.[9] Flow conditions beneath the shoaling wave remain essentially

---

[7]General relationships between bottom configuration and sediment transport are discussed by Munk (1949), Saville (1950), and Johnson (1953).

[8]Information on bar formation under natural conditions is limited, however there have been several excellent laboratory experiments. Examples of both can be seen in Keulegan (1944 and 1946), Shepard (1950), Bruun (1954), Rector (1954), Watts (1954), King (1959), Kemp (1960), and Hom-ma and Sonu (1963).

[9]References listed under Footnote 6 are applicable, especially Iverson (1952).

oscillatory with a net onshore component. Water motion progressively intensifies on the bottom in shallow water, subjecting exposed particles to increasing hydraulic force. When this force becomes great enough to overcome resistance of the sediment to movement, transportation results. Therefore, for any point within the zone of shoaling waves there is a depth, energy, material size ratio at which particles are influenced by forces capable of causing their movement.[10]

Hydraulic conditions associated with breaking waves are diverse and difficult to describe.[11] Breakers are clearly characterized by intense interaction with the bottom. As a wave breaks a plunging or spilling mass of water churns material off the bottom which is then carried by the translatory water as both suspended and bed load. Once placed in motion the particles are transported either onshore, offshore, or alongshore. Direction of movement becomes a function of material properties (size, shape, etc.) and the amount of direction of application of available energy. The final wave transformation occurs as the breaker becomes a translatory water body moving up the beach as swash.

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[10]The relationship between material transport and water motion associated with waves has been investigated by Li (1954), Ippen and Eagleson (1955), Manohar (1955), Eagleson, Dean, and Peralta (1958), Miller and Zeigler (1958), Hom-ma and Horikawa (1963), and Inman and Bowen (1963).

[11]For a description of velocity fields of shoaling and breaking waves, see Miller and Zeigler (1964).

The Subaerial Beach Zone

The subaerial beach includes a zone acted upon by swash forces, and a static portion of the deposit not affected by wave activity. The former corresponds morphologically with the beach-face, the latter with the backshore.

The general hydraulic character of the swash is an up and forward, down and backward motion, called uprush and backwash, which includes both turbulent and laminar flow. Briefly, after the wave breaks inshore, translatory water surges up the beach carrying finer sediment in suspension and coarser materials along the bottom. Return flow, beginning from zero velocity, is generally less turbulent and materials moving down slope are transported mostly as bed load. Swash activity is, however, complicated when the uprush of one wave meets the backwash of the preceding wave. Such a condition is actually more common than the idealized cycle described.

The linear to-and-fro swash action constantly redistributes beach-face sediment. If sediment carried by the uprush is approximately in balance with that moved by the backwash, equilibrium conditions exist. This is a dynamic equilibrium, of course, as all tidal beaches are subject to constant change. The main factors determining balance between erosion and deposition are: (1) beach-face slope, (2) material size, and (3) swash energy.

Since the swash zone is the most accessible segment of the system it has naturally received considerable attention. Vaughan Cornish discussed the association between wave action and beach slopes as early as 1898, and Fenneman (1902, p. 1) defined the equilibrium profile as that "which the water would ultimately impart, if allowed to carry its work to completion." Lewis (1931) was one of the first observers to record the relationship between erosion, deposition, and varying swash conditions on a natural beach. More recent field investigations on the general characteristics of the beach-face include Bascom (1951 and 1953), Bruun (1954), Miller and Zeigler (1958), Sitarz (1960), and Strahler (1964). Equally important laboratory studies are those of Bagnold (1940), Johnson (1949), Rector (1954), Watts and Dearduff (1954), King (1959), Kemp (1960), Johnsen (1961), and Iwagaki and Noda (1963). Although differences are expressed among these workers concerning association between elements of the subaerial beach zone, certain generalizations are possible. First, if beach material properties are constant, the intensity of swash action determines the equilibrium gradient. Conversely, if swash is constant, coarser sediment results in steeper gradients and finer sediments are associated with flatter gradients. However, as the gradient becomes steeper and the sediment coarser, swash energy is reduced by gravity and percolation which, in turn, establishes a steeper equilibrium slope. Thus, swash and beach material properties are the basic controls for the deposit's configuration, but the configuration itself contributes a strong "feed-back" factor to this association.

In summary, the beach-energy model describes a series of tightly linked physical interactions between (1) the hydraulic forces associated with wave deformation, (2) morphologic properties of the deposit, (3) properties of constituent particles of the deposit, and (4) the changing focus of the hydraulic forces as determined by the still-water level (see Fig. 3). The objective of this experiment is therefore measurement of these factors and determination of association between them.

SUMMARY DIAGRAM OF COMPLETED BEACH-ENERGY MODEL

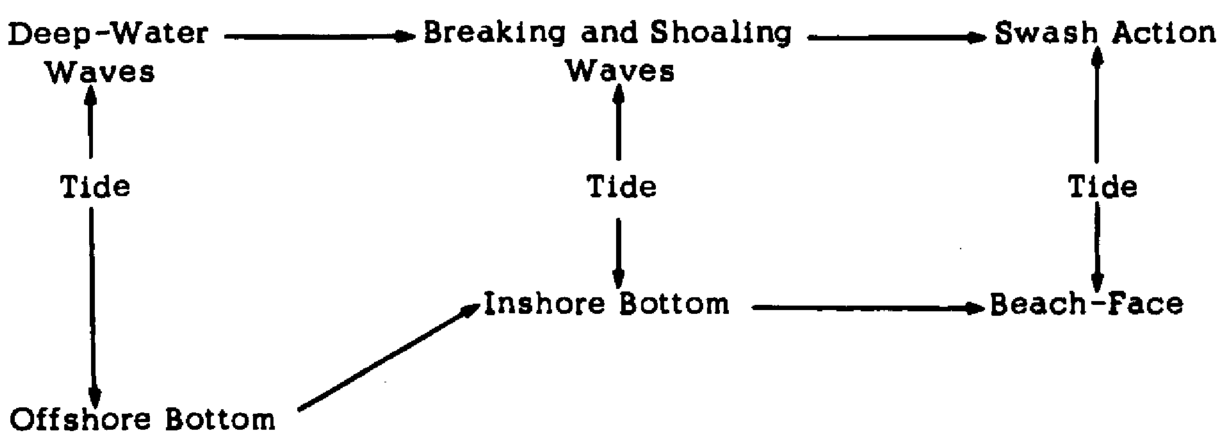

Figure 3. Summary of beach-energy model.

THE EXPERIMENTAL DESIGN

To compare interactions of the conceptual model with process-response relationships in nature, a series of field experiments were conducted during early spring of 1962 along coastal North Carolina.[12] This portion of the Atlantic Coast is suitable in several respects for a study of shoreline processes. Bodie Island is one of the isolated barrier islands known as the "Outer Banks" (Fig. 4) and thus fully exposed to North Atlantic waves. The tide is semi-diurnal, with an average range of about 3 feet. The beaches are narrow, moderately steep (Fig. 5), and composed of both quartz sand and gravel. Rapid changes in beach characteristics are particularly common during winter and spring when the area is influenced by "northeast storms."

Measurements of the Beach-Energy System

The model of process-response relationships developed in the previous section presents a greatly simplified explanation of a highly complex system of closely associated interactions. Actual measurement and testing in nature of even this very generalized model is, however, far from a simple task. In the Bodie Island experiments, the

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[12] Field work was begun in January 1962 with plans to continue through April 1962. On March 7, 1962 a severe storm (see Footnote 1) destroyed the experimental site and most essential field equipment.

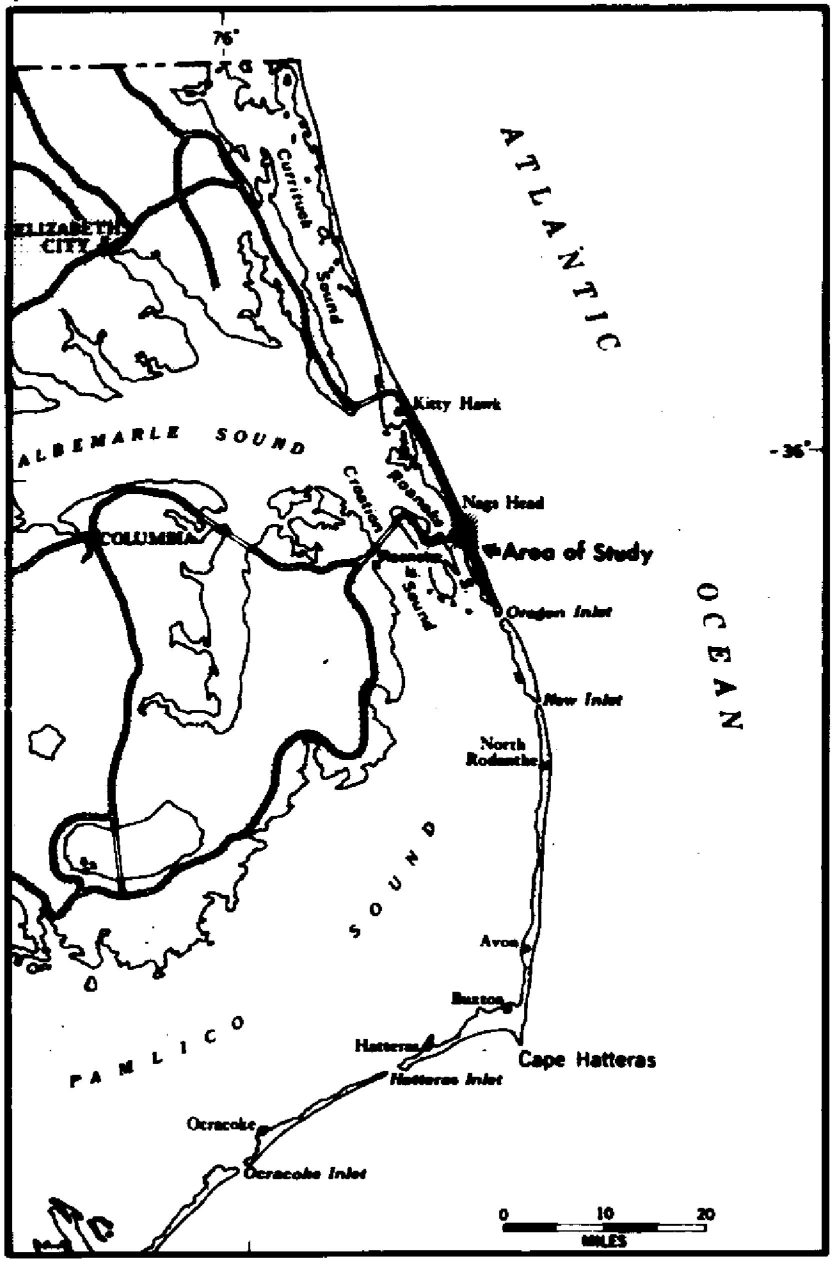

Figure 4. Location map of the Outer Banks, North Carolina.

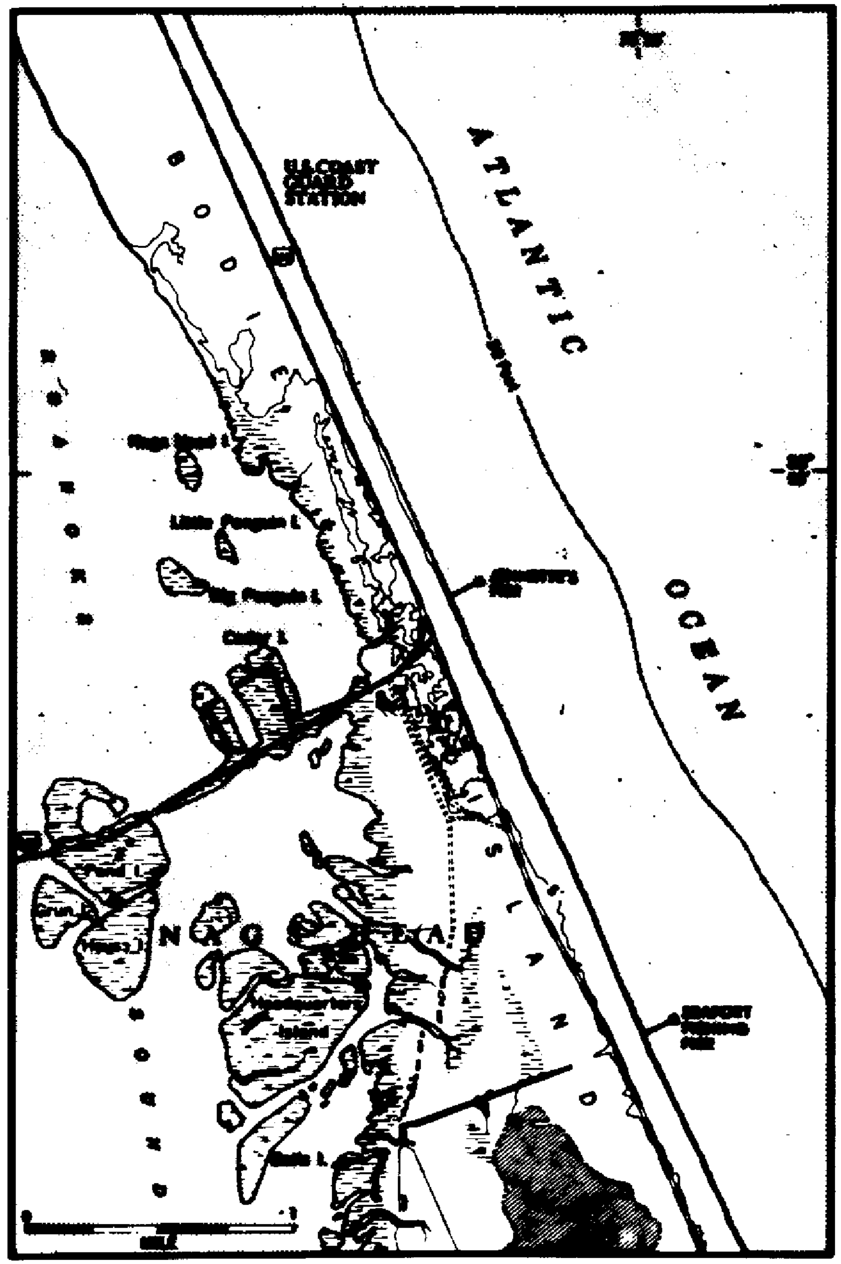

Figure 5. Detailed map of Bodie Island, North Carolina.

beach below lowest tide level was physically beyond the range of measurement and thus studies of beach responses to hydraulic forces were concentrated in the area between low tide and the limit of wave uprush. Likewise, the absences of significant theoretical or technical knowledge about breaking waves and swash excluded these energy factors from the experiments. Finally, consideration of the complete beach system must include the continuous nature of the energy application and beach response. During the Bodie Island investigation this could only be sampled at limited intervals, namely, 8:00 A.M., 12:00 Noon, and 4:00 P.M.

Measuremements were therefore limited to temporarily and spacially isolated segments of the total system. Energy was estimated from properties of essentially unbroken waves: wave height, wave period, and wave direction. Beach morphology was restricted to characteristics of the exposed subaerial beach deposit, which included measurements of beach thickness, beach width, beach-face slope, and the size and sorting of beach sediment. A schematic diagram of these measurements and their interrelationship is shown in Figure 6.

SUMMARY OF EXPERIMENTAL DESIGN

THE ENERGY FACTORS		THE RESPONSE FACTORS
Wave Height	Interactions	Beach Thickness
Wave Direction		Beach Width
		Beach Slope
Wave Period	Reactions	Sediment Size
Still-Water Level		Sediment Sorting

Figure 6. Schematic diagram of beach-energy design (after Krumbein, 1961).

Measurement of the Energy Factors

Wave height and wave period, which are directly related to the energy reaching the beach-face,[13] were recorded with a pressure-type wave gage,[14] mounted in about 15 feet of water at the end of a 650 foot long commercial fishing pier (Fig. 7). Wave height was estimated from the pressure gage records to the nearest 1/10 foot and wave period to

[13]For detailed discussion of wave energy, see O'Brien and Mason (1942), and Beach Erosion Board (1961).

[14]The wave gage was supplied by the Beach Erosion Board, Washington, D. C. For description of gage and record analysis, see Caldwell (1948), Snodgrass (1950 and 1952), Beach Erosion Board (1952), and Putz (1953).

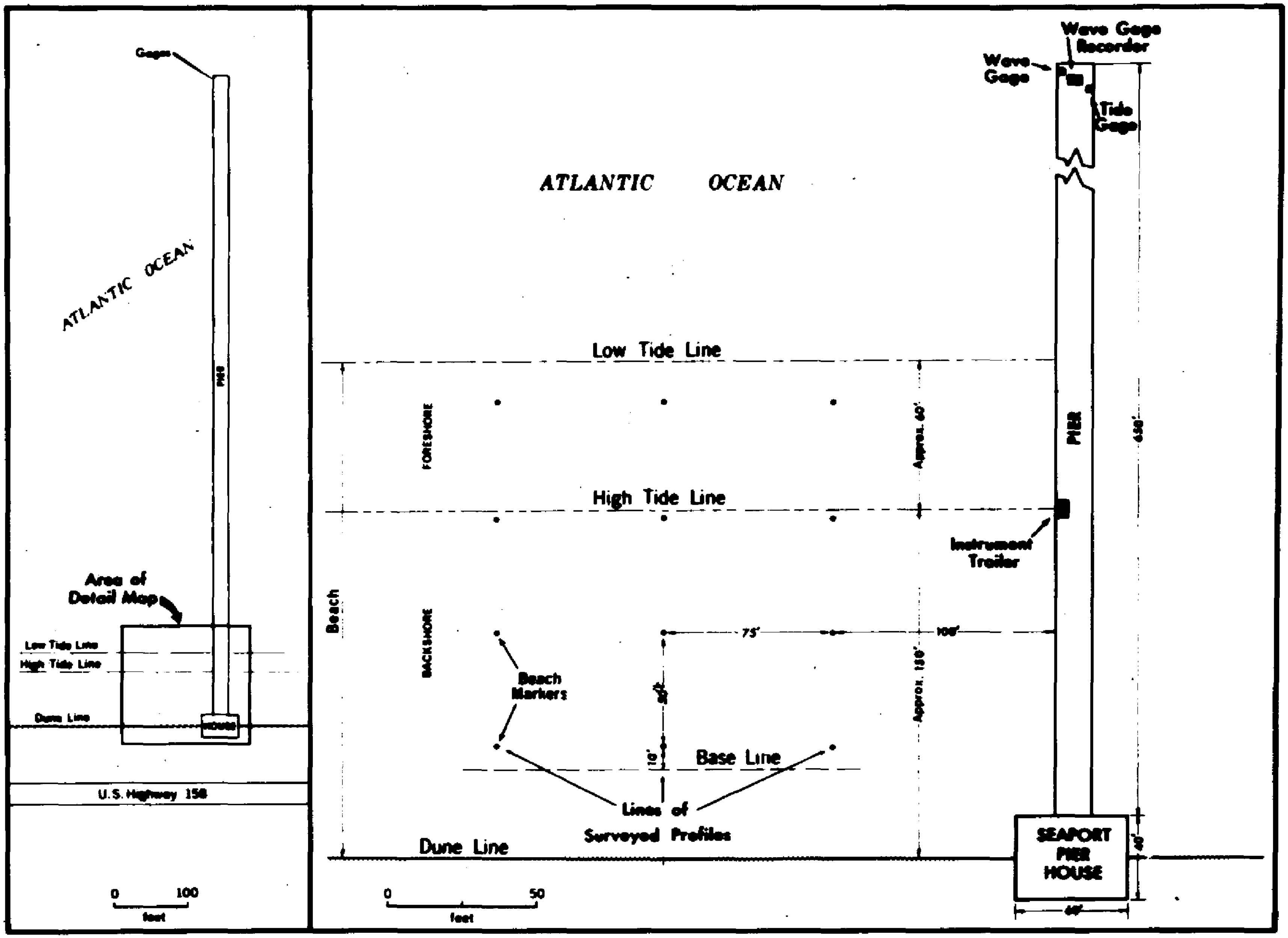

Figure 7. Detailed map of the Seaport Fishing Pier and the general area of the experimental site.

the nearest second. Wave direction was estimated to within 5^{o} with a pocket transit fitted with a simple sighting bar.[15] Still-water variation was recorded to the nearest 1/10 foot with a standard automatic portable tide gage.[16]

Measurement of the Response Factors

The arrangement of measurement sites for the response factors is shown in Figure 8. Beach thickness is represented by the distance above mean sea level of points along three traverses at right angles to the shoreline. Beach width is the distance from base-line to the point of intersection of mean sea level and the beach surface. Beach-face slope is the measured gradient between the points of beach thickness. Thickness was measured to the nearest 1/10 foot, width to the nearest foot, and slope expressed as tangent for the elevation differences between points of thickness. A summary of the raw energy and response data is given in Appendix I.

Beach measurements were made along three closely spaced traverses located within an area measuring 150 feet parallel by about 125 feet normal to the strandline as shown in Figure 7. Beach profile

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[15]Forrest (1950) demonstrated in a similar application that this technique is accurate to within 5^{o}.

[16]The tide gage was installed by the Corps of Engineers, Wilmington District, North Carolina.

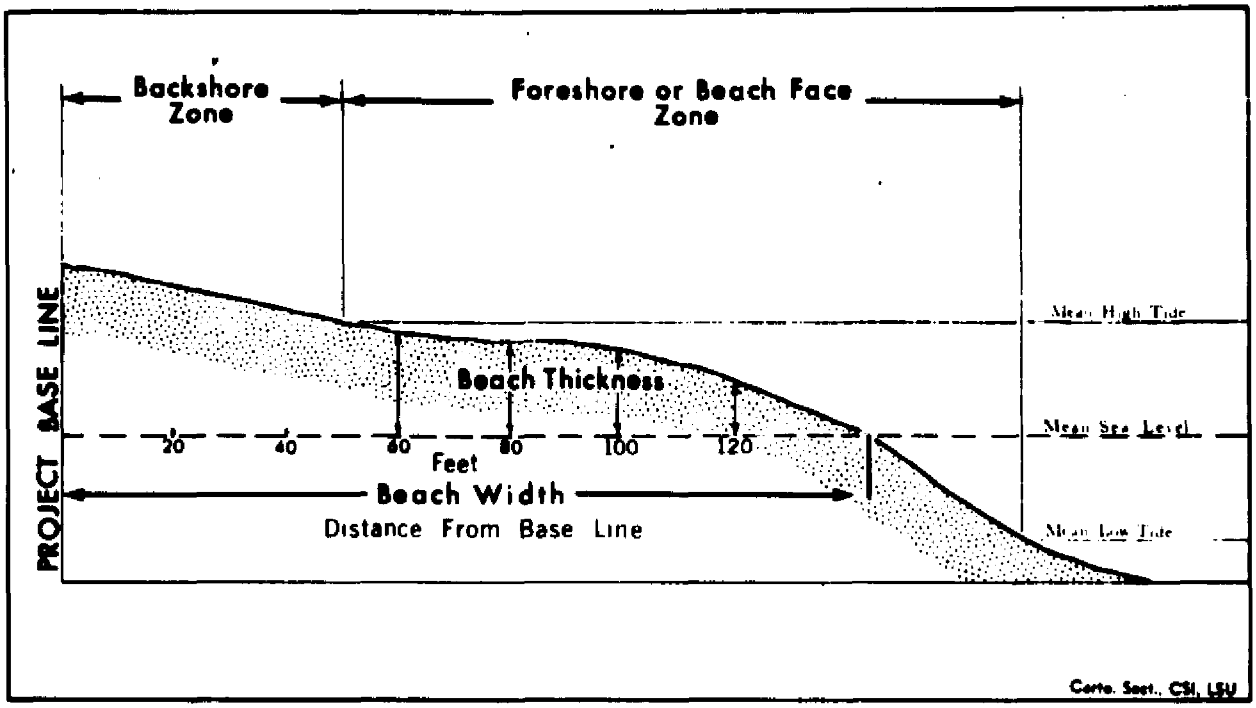

Figure 8. Hypothetical profile showing relationships between the response measurements.

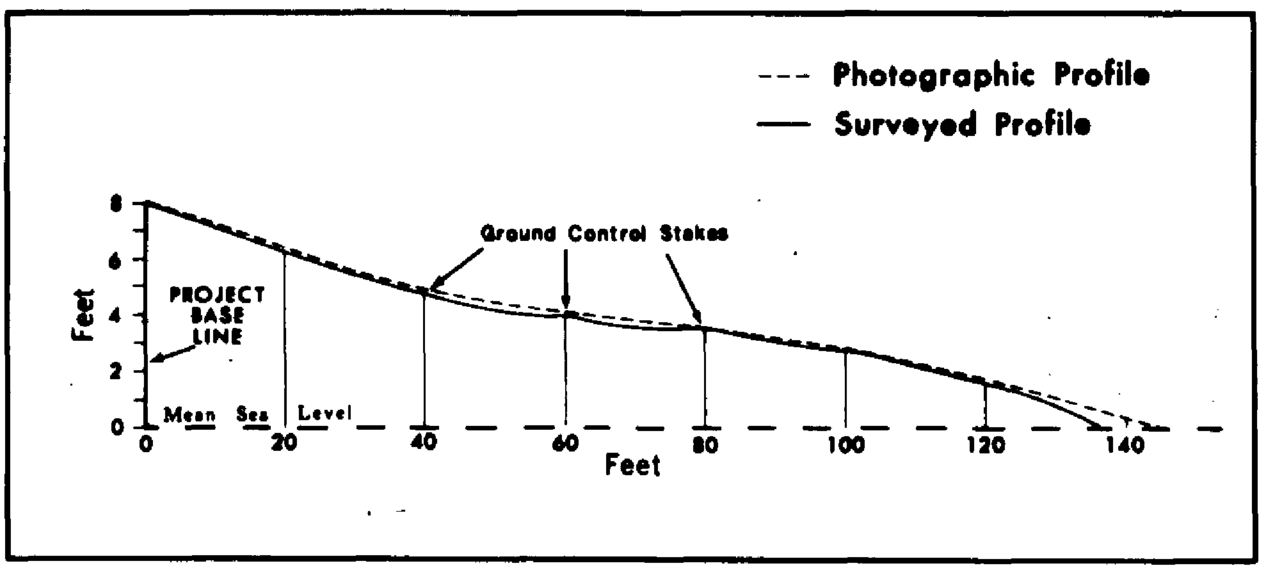

Figure 9. Comparison profiles of surveyed and photographic traverses.

measurements included conventionally surveyed profiles, taken daily during the lowest tidal stages, and profiles interpreted from 35 mm sequence photography. The photographic application was an experiment to determine if accurate profiles (sand levels) could be obtained with a less laborious technique.

The Photographic Application. Briefly, the principle of the photo profiling application was that sand thickness for positions across the beach could be determined from oblique photographs of graduated ground control markers. Operationally, the technique is as follows: An automatic camera, placed on the pier (Fig. 10b), is programmed to take sequence photos of the beach in profile. Close-ups of images thus recorded are projected onto a screen from which the sand levels are measured relative to an array of ground control markers (Fig. 10c). Finally, these points are plotted in the standard graphic form. An example of such a profile is shown in Figure 9 which compares a photographic profile based on 8 control points which surveyed results of the same traverse based on 20 points. In addition, the sequence photos provided an excellent record of sediment patterns and general beach conditions. Generally, coarse-textured materials recorded a lighter tone, and fine-textured darker.

The sequence camera was a 35 mm Nikon Model F, fitted with a 250 exposure magazine, and electric motor drive (Fig. 10d). The lens type was varied according to the state-of-the-beach. For high waves

Figure 10a. General view of beach in vicinity of experimental site, Bodie Island, North Carolina.

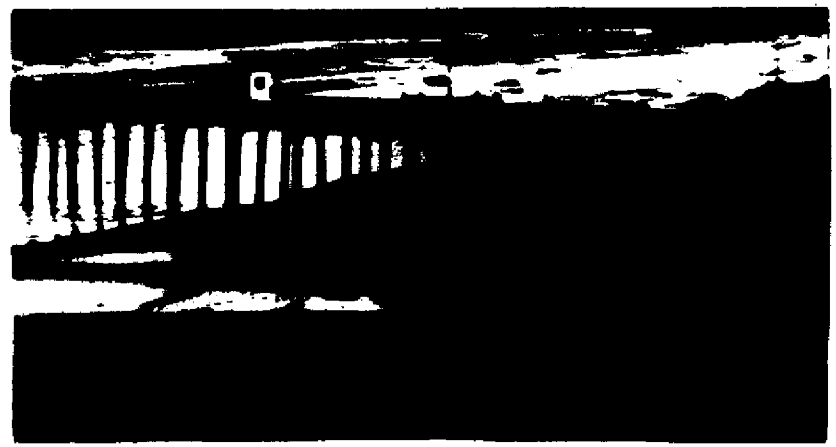

Figure 10b. Seaport Fishing Pier with camera trailer in position.

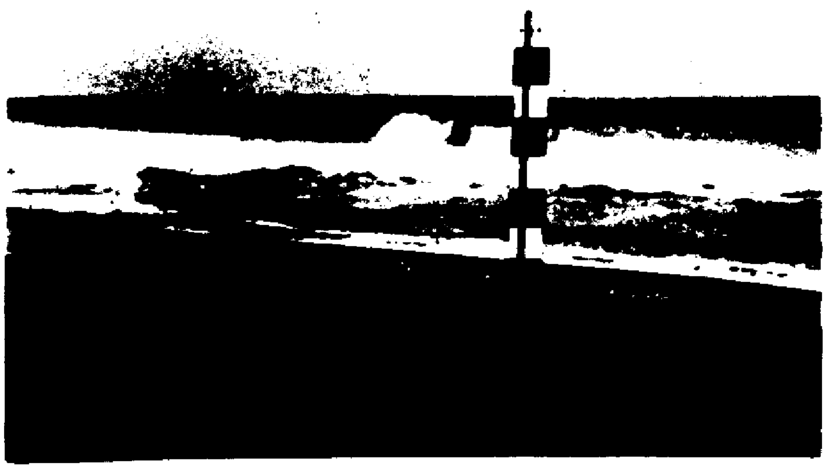

Figure 10c. Ground control marker for photographic application.

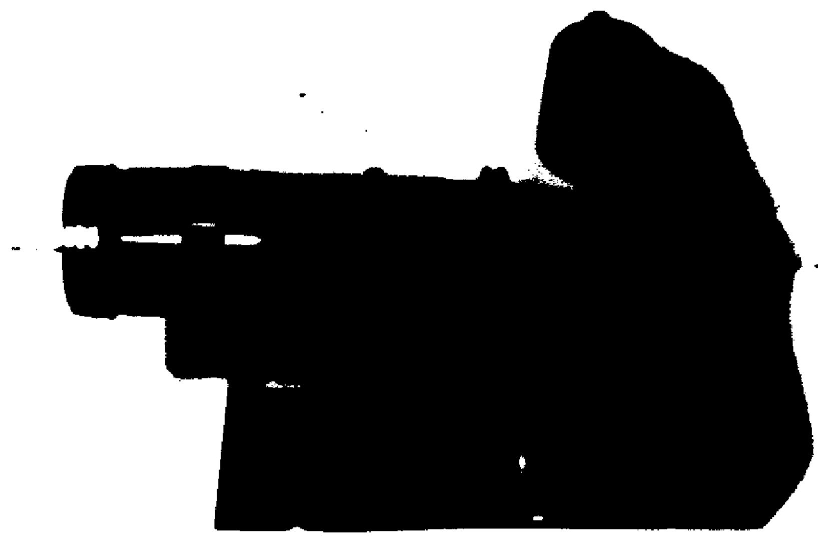

Figure 10d. Nikon 35 mm automatic camera with accessories.

and a wide beach a 50 to 85 mm lens was found to be appropriate; whereas, during calms, with narrow swash-zones, a moderately long telephoto lens (125-175 mm) gave better results.

Elimination of over-and-under exposure because of rapidly changing light conditions was accomplished with an Autex Exposure Control, manufactured by Flight Research, Richmond, Virginia. The photographic operation was synchronized with wave, tide, and other aspects of the beach experiment through utilization of a CECO Model 640-A Programming Device manufactured by Camera Equipment Company, New York.

Beach Sediment Sampling. The specific objective of collecting swash-zone sediment samples was to determine whether properties (size and sorting) of the sedimentary particles were associated with changes in beach morphology and wave energy. This information was obtained from samples collected at the lowest tidal stage of each sampling day. The frequency in sampling was based on variance estimates according to a method described by Cochran, in Snedecor (1956, p. 489).

The sediment sampling was confined to the area which had been the swash zone during the preceding high tide. Simple random clusters of grains were taken from the surficial one-inch of the beach. Each sample consisted of about 250 grains collected with a series of increment sampling tools designed to obtain a small volume of sample for small grains, and a larger volume for larger grains. In this way a degree of consistency was maintained for depth of sampling and the number of grains collected.

Each sample was washed, dried, and split into amounts suitable for mounting on glass slides. A Ken-A-Vision Micro-Projector provided images for tracing grain outlines. The first 20 grains encountered along traverses made at random coordinates were selected for measurement. Particles too large for projection were measured with calipers.

For each grain profile the longest, or A-axis, and the longest dimension perpendicular to that, or B-axis, were measured. Mean grain size and standard deviation for each sample were then determined from calculations of the B-axes.

ANALYSIS OF THE OBSERVATIONAL DATA

Although the conceptual model describes the general relationships between elements of the beach-energy system, statistical analysis of the experimental data provides a quantitative assessment of both the existence and degree of these interactions. Specifically, the analysis was designed to answer the following questions:

(1) Is there a significant correlation between the energy factors, or can these factors be treated as independent variables without introducing redundancy in the analysis?

(2) To what degree are the response factors interrelated? Also, where similar measurements are made on closely adjoining beach profiles, can these measurements be combined and utilized as a single measurement?

(3) If the energy factors are independent then what is the degree of interaction between them and each of the responses? Is there an order of significance among the processes in explaining variation in the responses?

Statistical Methods

Examination of scatter plots of process and response measurements indicated that although considerable dispersion exists in the Bodie Island data there is no reason to assume non-linear relationships (Fig. 11). Therefore, since the objective of this study is determination of association between complex variables, the form of analysis was linear correlation and regression. This included calculation of: correlation coefficients ("r and R"), which are measures of the relative degree of association between two or more variables; coefficients of determination ("r^2 and R^2"), which show the proportion of response variation attributable to association with the processes; and, variance ratio ("F-tests") tests which establish whether the associations are statistically significant. A brief outline of these methods is included in Appendix II, but any standard statistical handbook, e.g. Snedecor (1956), would serve equally well. Papers describing direct application of these and similar methods to beach problems are given in several papers by Krumbein, especially Beach Erosion Board Memo. 130 (1961).

Association Between Energy Factors

Table I is a numerical summary of the energy factors, and the association between these variables is shown in the correlation matrix

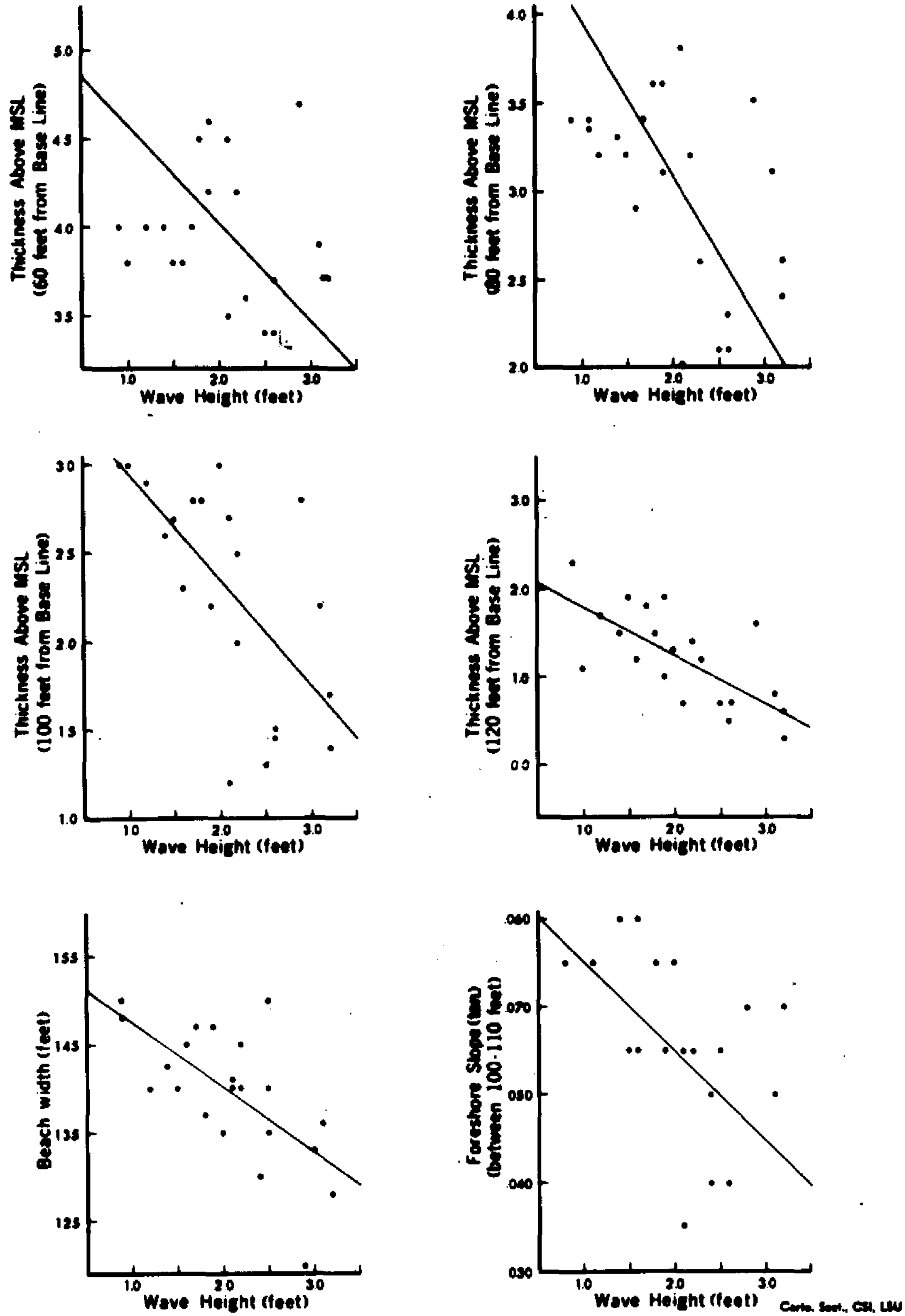

Figure 11. Scatter diagrams for selected response wave height interactions.

on Table II. These latter results clearly indicate that the four processes are not strongly interrelated and, therefore, in testing process-response interactions the energy factors can be considered independently.

TABLE I

SUMMARY OF THE PROCESSES

	High Value	Low Value	Mean Value
Wave Height	3.2 ft.	0.9 ft.	2.0 ft.
Wave Period	10.0 sec.	5.5 sec.	7.2 sec.
Wave Direction	15.0°	0.0°	4.5°
Still-Water Level	+3.4 ft.	-0.4 ft.	+2.8 ft.

TABLE II

CORRELATION MATRIX FOR THE PROCESSES

	X_1	X_2	X_3	X_4
X_1 Wave Height	-	.07	-.04	-.28
X_2 Wave Period	-	-	.03	.16
X_3 Wave Direction	-	-	-	-.02
X_4 Still-Water Level	-	-	-	-

Association Between Response Factors

Table III summarizes the response or dependent factors, and Figure 7 shows the position of the measurement sites for each of

TABLE III

SUMMARY OF RESPONSES

	High Value	Low Value	Mean Value
Beach Thickness:			
60'	4.7 feet	3.4 feet	3.9 feet
80'	3.8 feet	2.0 feet	3.0 feet
100'	3.0 feet	1.2 feet	2.2 feet
120'	2.3 feet	0.3 feet	1.2 feet
Beach Slope:			
60'- 80'	.120 (tan)	.025 (tan)	.051 (tan)
80'- 100'	.065 (tan)	.025 (tan)	.043 (tan)
100'- 120'	.080 (tan)	.020 (tan)	.055 (tan)
Beach Width	150 feet	125 feet	139 feet
Beach Sediment Size	2.31 mm	.25 mm	.72 mm
Beach Sediment Sorting	1.14	.11	.29

these variables. Because measurements of beach thickness, width, and slope were replicated along parallel traverses, analysis of variance was used to determine whether these data could be combined into a single set of response measurements. Table IV is an example of these tests for beach thickness 110 feet from the baseline. This particular test, as well as others for the remaining measurements, shows no significant variation introduced by treating the profiles collectively. This means that variation between points along the beach is of little significance when compared to variation from measurement period to measurement period.[17]

TABLE IV

ANALYSIS OF VARIANCE FOR THICKNESS 110 FEET FROM THE BASELINE

Source	Sum of Squares	d.f.	Mean Squares	F
Between Measurements - Within Profiles	23.16	60	.386	5.15**
Between Profiles - Along the Beach	00.15	2	.075	
Total	23.31	62		

Table V is the correlation matrix for the response factors. Points of beach thickness show positive correlation; a predictable outcome since thickness on all parts of the beach would be expected to respond together. Associations between thickness and slopes are, for the most part, significant. The other responses, including sediment property - slope associations, are either weakly or not significantly related. The

[17]Similar results are reported by Krumbein and Miller (1953), and Krumbein (1961).

TABLE V

CORRELATION MATRIX FOR RESPONSE

		Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Y_9	Y_{10}
Y_1	Thickness - 60'	--	.85	.72	.58	-.33	-.28	.67	.30	.22	.15
Y_2	Thickness - 80'	--	--	.94	.76	-.10	-.67	.76	.87	.39	.23
Y_3	Thickness - 100'	--	--	--	.86	-.09	-.75	.66	.53	.31	.21
Y_4	Thickness - 120'	--	--	--	--	-.31	-.68	.27	.62	.33	.24
Y_5	Slope - 60' to 80'	--	--	--	--	--	-.20	-.04	-.24	-.02	.08
Y_6	Slope - 80' to 100'	--	--	--	--	--	--	.47	-.24	-.55	.07
Y_7	Slope - 100' to 120'	--	--	--	--	--	--	--	.02	.24	.17
Y_8	Beach Width	--	--	--	--	--	--	--	--	-.19	.09
Y_9	Sediment Size	--	--	--	--	--	--	--	--	--	.46
Y_{10}	Sediment Sorting	--	--	--	--	--	--	--	--	--	--

latter results, believed to be functions of improper sediment, will be discussed in a later section.

Relationship Between the Energy Factors and the Responses

Certain specific hypotheses for process-response interactions may be expected from the beach energy model: First, the external characteristics of the beach are expected to respond inversely to the hydraulic forces of the energy factors. That is, higher waves, greater number of waves (shorter periods), and increased angle of incidence should be closely related to reductions in beach thickness, beach width, and beach-face slopes. Similarly, lower waves with longer periods and lower angle of incidence should be associated with thick, wide, and steep beaches. The role of still-water level, that is, short term tidal conditions, as an "energy" mechanism should be expected to vary with respect to its intersection with the beach-face. The lower beach is thus more or less constantly subject to variations in wave activity and still-water level should have little effect; however, the upper beach can respond only when elevated still-water levels bring this area under direct swash action. Second, the internal characteristics of the beach are interrelated to both the morphology and energy factors. Steeper beaches should be coarser, more poorly sorted, and occur with lower energy conditions; whereas, for those with flatter gradients, the reverse should be true. Although earlier steps in the analysis have shown a lack of significant correlations between sediment properties and slopes (Table V), a possibility remains that slope and sediment properties may be independently associated with the energy factors.

Beach Thickness - Energy Relationships

Table VI gives the results of multiple-regression analysis for relationships between beach thickness and energy factors. F-tests indicate significant correlations between thickness at all beach positions and the energy factors; furthermore, the R^2 values show that wave height and still-water level are the most influential processes. Together they account for about 75 per cent of the total variation in thickness; the remaining 25 per cent being distributed between wave period and wave direction. These findings are in close agreement with Bagnold's (1940) and Kemp's (1960) empirical wave-tank experiments, and Bascom's (1953) extensive field observations.

The role of still-water level relative to changes in beach thickness is more clearly illustrated in Table VII, which summarizes the statistical data from Table VI. Essentially, these results substantiate the expectation that variations in sand level along the lower beach (100'-120') are reflective primarily of continuous wave action, whereas, in the upper beach (60'-80'), swash forces are effective only during times of higher still-water levels.

TABLE VI

MULTIPLE-REGRESSION ANALYSES FOR BEACH THICKNESS

	Processes				R^2	R	F	Percent of Total Explained Variance
	Still-water	Wave Height	Period	Direction	.74	.86	11.9**	100
	Still-water	Wave Height	Period	--------	.74	.86	16.6**	100
60 feet	Still-water	Wave Height	------	---- --	.74	.86	25.6**	100
	Still-water	---- ------	------	--------	.58	.76	26.7**	78
	Still-water	Wave Height	Period	Direction	.77	.88	13.7**	100
	Still-water	Wave Height	Period	--------	.76	.87	18.3**	98
80 feet	Still-water	Wave Height	------	--------	.69	.83	20.7**	89
	Still-water	----- -----	------	--------	.46	.68	6.9*	59
	Wave Height	Still-water	Direction	Period	.85	.92	21.9**	100
	Wave Height	Still-water	Direction	------	.84	.92	31.0**	98
100 feet	Wave Height	Still-water	--------	------	.80	.89	36.1**	94
	Wave Height	---------	--------	------	.42	.65	14.1**	49
	Wave Height	Still-water	Direction	Period	.75	.87	12.2**	100
	Wave Height	Still-water	Direction	------	.75	.87	17.1**	100
120 feet	Wave Height	Still-water	--------	------	.69	.83	20.3**	92
	Wave Height	---------	--------	------	.49	.70	18.5**	65

**Significant at the .01 level.

NOTE: In interpreting this and subsequent tables, a systematic decrease in the number of variables included in each stage of the analysis should be noted. Sequential step-wise deletion starts with four variables, withdrawal of the least significant based on the F-test, and re-analysis of the remaining.

TABLE VII

APPROXIMATE* EXPLAINED VARIATION IN BEACH THICKNESS ATTRIBUTABLE TO WAVE HEIGHT AND STILL-WATER LEVEL

Position	Wave Height (H 1/3)	Still-Water Level (Tide)
60 Feet	22%	78%
80 Feet	33%	67%
100 Feet	52%	48%
120 Feet	71%	29%

*There is an established correlation between wave height and still-water level (Table II).

Beach Width - Energy Relationships

Variance ratio tests on Table VIII indicate significant correlations between beach width and the energy factors. As in the case of beach thickness, wave height and still-water level are obviously the most significant variables, together accounting for over two-thirds of the total explained variance. The R^2 values are, however, more evenly distributed, suggesting that all the processes play some significant part in the association. This relatively even distribution of the influence of energy factors on beach width compared to the generally uneven levels for beach thickness probably arises from differences in measurement techniques. Thickness of the beach varied only when the tide brought swash action to the fixed sand level positions, whereas,

TABLE VIII

MULTIPLE-REGRESSION ANALYSIS FOR BEACH WIDTH

	Processes				R^2	R	F	Percent of Total Explained Variance
	Wave Height	Still-Water	Period	Direction	.51	.72	4.2*	100
Width	Wave Height	Still-Water	Period	--------	.46	.68	4.8*	90
	Wave Height	Still-Water	------	--------	.35	.59	4.9*	68
	Wave Height	----------			.19	.43	4.5*	37

*Significant at the .05 level.

TABLE IX

MULTIPLE-REGRESSION ANALYSES FOR SEDIMENT SIZE AND SORTING

	Processes				R^2	R	F	Percent of Total Explained Variance
	Wave Height	Period	Still-Water	Direction	.12	.35	0.5 NS	100
Sediment Size	Wave Height	Period	Still-Water	--------	.12	.35	0.8 NS	100
	Wave Height	Period	---------	--------	.12	.35	1.2 NS	100
	Wave Height	------	---------	--------	.10	.32	2.1 NS	83
	Wave Height	Period	Still-Water	Direction	.09	.31	0.3 NS	100
Sediment Sorting	Wave Height	Period	Still-Water	--------	.09	.31	0.5 NS	100
	Wave Height	Period	----------	--------	.08	.29	0.9 NS	88
	Wave Height	------	----------	--------	.06	.25	1.1 NS	66

*Significant at the .05 level.
NS - Not significant.

beach width was measured between a fixed backshore location and the intersection of the beach-face and mean still-water level (literally, mean sea level). Therefore, beach width reflects an area more or less continuously under wave influence and thus is more sensitive even to those minor factors which contribute to the total effect of wave action.

Beach Slope, Sediment, Energy Relationships

Bascom (1951, p. 100) has described the relationship between waves, sediment, and beach slopes as follows: "The slope of the beach-face will change, even though the sand size is unchanged, if wave conditions change. The rule is simple: Beaches flatten as they erode and steepen as they build." Although simplicity of the rule might be questioned[18] results of the Bodie Island experiment shown in Table X support Bascom's statement, i.e. slopes flatten with increased energy and steepen with decreased energy. Among the energy factors, wave height and still-water level are the main controls of beach-face slope variance; whereas, wave period and direction are of minor importance.

Unlike beach-face slope or any of the other responses, sediment properties show little association with the energy factors. Table IX illustrates this relationship by very low R^2 values, as well as non-significant F-tests. Such outcomes are not consistent either with the

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[18]For example, see Iwagaki and Noda (1963, p. 200).

TABLE X

MULTIPLE-REGRESSION ANALYSES FOR BEACH-FACE SLOPE

	Processes				R^2	R	F	Percent of Total Explained Variance
60-80 feet	Still-water	Wave Height	Period	Direction	.21	.46	1.0 NS	100
	Still-water	Wave Height	Period	--------	.21	.46	1.5 NS	100
	Still-water	Wave Height	------	--------	.21	.46	2.3 NS	100
	Still-water	-----------	------	--------	.19	.43	4.4 *	89
80-199 feet	Wave Height	Still-water	Period	Direction	.55	.74	4.9 **	100
	Wave Height	Still-water	Period	--------	.55	.74	6.9 **	100
	Wave Height	Still-water	------	--------	.54	.73	10.5 **	98
	Wave Height	---------	------	--------	.41	.64	13.4 **	74
100-120 feet	Wave Height	Still-water	Period	Direction	.43	.66	3.1 *	100
	Wave Height	Still-water	Period	--------	.43	.66	4.3 *	100
	Wave Height	Still-water	------	--------	.36	.60	5.0 *	83
	Wave Height	---------	------	--------	.27	.52	7.2 *	62

NS - Not significant.
** - Significant at the .01 level.
* - Significant at the .05 level.

conceptual model or published experimental results (see references listed on page 7). This lack of association of sediment and energy in the Bodie Island experiment, coupled with the unexpected lack of correlation of slope and sediment properties (Table IV), suggests that the sediment samples may have relatively little relation with the actual deposit. This opinion has since been verified in unpublished experiments by Meland, Ferm, and Dolan.

Unexplained Variance - Discussion

Although most of the process-response associations in the Bodie Island experiments were statistically significant, the level of unexplained variance is relatively high. Tables VI through X, which summarize the analysis, show that the magnitude of residual variation ranges from 20 to 90 per cent, and averages about 50 per cent. The following explanations are suggested for part of this unassigned variation:

(1) A significant part of the residual is probably associated with variables not included in the experiments. For example, swash action, which has been described as the most direct link between wave and beach changes, could not for technical and theoretical reasons be included in this study. Such unmeasured factors provide bias in one way or another, or simply contribute a very high noise level to the data.

(2) In this experiment, the process-response interactions were considered as essentially instantaneous events. However, the energy system is subject to constant changes, and it may be assumed that a highly variable time-delay occurs between changes in the processes and re-establishment of beach-face equilibrium.[19] Theoretically, the length of time-delay for a particular wave-tide-beach regime would depend on: (a) the amount and properties of the beach material to be modified, and (b) the energy available to accomplish the modification.

(3) In final appraisal of the sediment design, a significant level of sampling error is found; that is, the samples provided only a very imprecise estimate of the parent population. Increased reliability would have required many more samples. Equally and perhaps more important, the samples were biased in that the depth (thickness) at which they were taken was fixed arbitrarily rather than based on the material effected by swash forces during the sampling period.

(4) Finally, regardless of how carefully the experiment has been designed, the results can be no better than its execution, and undetected errors in the measurements are carried through to the final results.

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[19]Krumbein (1961) reports the average time-lag for Pacific Coast beaches is on the order of 6 hours.

SUMMARY AND CONCLUSIONS

This study was undertaken to determine the degree of association between surf-zone processes and morphologic characteristics of a natural beach on Bodie Island, North Carolina. The wave-tide-beach relationships are described in terms of a system of interactions between (1) the hydraulic forces associated with wave deformation, (2) variations in still-water level, and (3) the configuration and internal properties of the beach deposit itself.

The measurements were limited to temporarily and spacially isolated segments of the total beach-energy system. Energy, including distribution relative to the beach-face, was estimated from measurements of wave height, wave period, wave direction, and still-water level. Beach morphology was restricted to properties of the subaerial beach deposit, and included beach thickness, width, slopes, and sediment properties.

Hypotheses for specific process-response interactions were tested with multiple-regression analysis. Cumulative coefficients of determination ranged from 0.85 for beach thickness, energy associations, to 0.09 for sediment property, energy relationships. Of the energy factors selected, wave height and still-water level were most significant. Wave period and wave direction were of less importance. Therefore, although some of the interactions are not as strong as initially assumed, the conceptual model is in reasonable agreement with the Bodie Island natural beach data.

Major sources for the residual variance can be attributed to (1) omission of important variables from the experiment, (2) inadequacies in the sampling design, (3) the time-delay between changes in the process intensity and resulting beach-face adjustments, and (4) undetected measurement errors.

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APPENDIX I

RAW DATA SUMMARY

Date	X_1	X_2	X_3	X_4	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Y_9	Y_{10}
2- 9-62	1.0	7.7	05	+0.5	3.8	3.4	3.0	1.1	.120	.035	.070	145	0.29	.127
2-10-62	3.1	6.0	13	+1.3	3.9	3.1	2.2	0.8	.040	.035	.070	140	0.34	.122
2-11-62	3.2	6.0	05	+1.5	3.7	2.6	1.7	0.6	.065	.055	.055	130	0.82	.282
2-12-62	3.2	6.5	00	+1.3	3.7	2.4	1.4	0.3	.065	.060	.060	125	0.37	.377
2-13-62	2.6	6.0	00	-0.1	3.7	2.3	1.5	0.5	.060	.055	.055	131	0.25	.137
2-14-62	2.1	6.0	02	-0.4	3.5	2.0	1.2	0.7	.060	.065	.025	140	0.32	.142
2-15-62	2.5	8.0	05	-0.1	3.4	2.1	1.3	0.7	.060	.055	.030	140	0.75	.262
2-16-62	2.6	10.0	00	+0.5	3.4	2.1	1.5	0.7	.040	.050	.040	140	0.42	.175
2-17-62	2.3	10.0	05	+0.7	3.6	2.6	2.0	1.2	.040	.045	.040	143	0.51	.345
2-18-62	1.6	5.5	00	+1.0	3.8	2.9	2.3	1.2	.040	.045	.060	145	0.91	.370
2-19-62	1.5	5.5	08	+0.6	3.8	3.2	2.7	1.9	.040	.040	.050	143	0.84	.229
2-20-62	1.2	6.0	00	+1.0	4.0	3.2	2.9	1.7	.040	.030	.070	140	0.60	.302
2-21-62	1.4	6.5	00	+0.2	4.0	3.3	2.6	1.5	.060	.025	.060	135	2.31	1.226
2-22-62	1.7	7.0	15	+0.2	4.0	3.4	2.8	1.8	.045	.025	.060	141	1.16	.402
2-23-62	0.9	8.0	10	+0.4	4.0	3.4	3.0	2.3	.060	.025	.040	145	0.86	.272
3- 1-62	1.9	7.5	10	+1.8	4.2	3.1	2.2	1.1	.060	.050	.050	140	0.30	.110
3- 2-62	2.2	9.5	05	+1.6	4.2	3.2	2.5	1.4	.060	.050	.060	143	0.45	.320
3- 3-62	2.1	7.3	05	+1.4	4.5	3.8	2.7	1.3	.060	.040	.080	135	1.65	1.142
3- 4-62	1.8	7.0	00	+1.5	4.5	3.6	2.8	1.5	.040	.040	.070	137	1.20	.517
3- 5-62	1.9	7.5	00	+2.5	4.6	3.6	3.0	1.9	.030	.050	.070	147	0.28	.110
3- 6-62	2.9	8.3	05	+3.4	4.7	3.5	2.8	1.9	.025	.050	.060	150	0.50	.160

APPENDIX II

STATISTICAL METHODS

Scatter diagrams were prepared for paired process and response variables. A rough estimate of association is simple when plotted points are well distributed along a line or path. However visual interpretation becomes more difficult as dispersion of points increases. When a line is fitted to a scatter diagram and all points can be connected, the correlation is functional - a rare occurrence in the earth sciences. In contrast, as scatter increases correlation decreases.

In most cases scatter points will not coincide perfectly with the best fitting line. By calculating deviation of each point from the line $[S_e^2 = \sum (y - y_e)^2]$, variability of y (dependent) not explained by regression is obtained. Thus, over-all variance of y summed and squared $[Sy^2 = \sum (y - \bar{y})^2]$ gives total sum of squares of the dependent variable. Of this total (Sy^2), part is explained variance (Sy'^2) and the remainder unexplained or residual variance (S_e^2), that is, $Sy^2 = S_e^2 + Sy'^2$. The square root of the ratio of explained variance (Sy'^2) to total variance (Sy^2) results in the correlation coefficient "r". This statistic may be used as a measure of association between two variables. Numerically, r never exceeds +1 or -1; if correlation is "weak," r will approach 0, if relatively "strong," the value of r will be closer to + or -1.

If the correlation coefficient is squared, the resulting statistic is called the coefficient of determination (r^2) and is the proportion of total variation of y explained by its relation with x (independent). Unexplained or residual variance may result from any number of factors, for example, measurement errors or variables not considered in the experiment.

A frequently used test of significance is the variance ratio or "F-test." The statistic F is a ratio of the mean squares of y related to x (Sy'^2) and mean squares of y not related to x (S_e^2), or

$$F = \frac{\text{Regression mean squares}}{\text{Residual mean squares}} .$$

If F is large enough at a predetermined significance level, the correlation is accepted as statistically significant. To determine whether an F value is sufficiently large, it is evaluated by standard F tables which are available in most statistical texts.

Multiple-regression tests association between one dependent and two or more independent variables. Although addition of independent variables to the regression model increases computation, procedures in analysis are essentially the same as those in simple linear correlation.

Several methods are available for testing strength of multiple correlation and regression (Ostle, 1954; Snedecor, 1959); however, in general, the multiple correlation coefficient "R" and coefficient of determination "R^2" may be interpreted in much the same form as in simple linear regression. The variance ratio or F-test is also used to test relative degrees of association.

VITA

Robert Dolan was born in Los Angeles, California, April 5, 1929. He attended John C. Fremont High School in that city. After two years in the United States Navy (1946-1948) he moved to Oregon, and in 1949 enrolled in Southern Oregon College, Ashland, Oregon. Following graduation in 1955 he entered Oregon State University and received a Master of Science degree in geography in 1957. He taught one year at Oregon State University before entering Louisiana State University as a candidate for the Ph.D. degree in physical geography and geology. While at Louisiana State University he has been a graduate assistant in geography and a research associate with Coastal Studies Institute. He is a member of Sigma Xi and the Association of American Geographers.

EXAMINATION AND THESIS REPORT

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Major Field: PHYSICAL GEOGRAPHY

Title of Thesis: RELATIONSHIPS BETWEEN NEARSHORE PROCESSES AND BEACH CHANGES ALONG THE OUTER BANKS OF NORTH CAROLINA

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

JANUARY 4, 1965